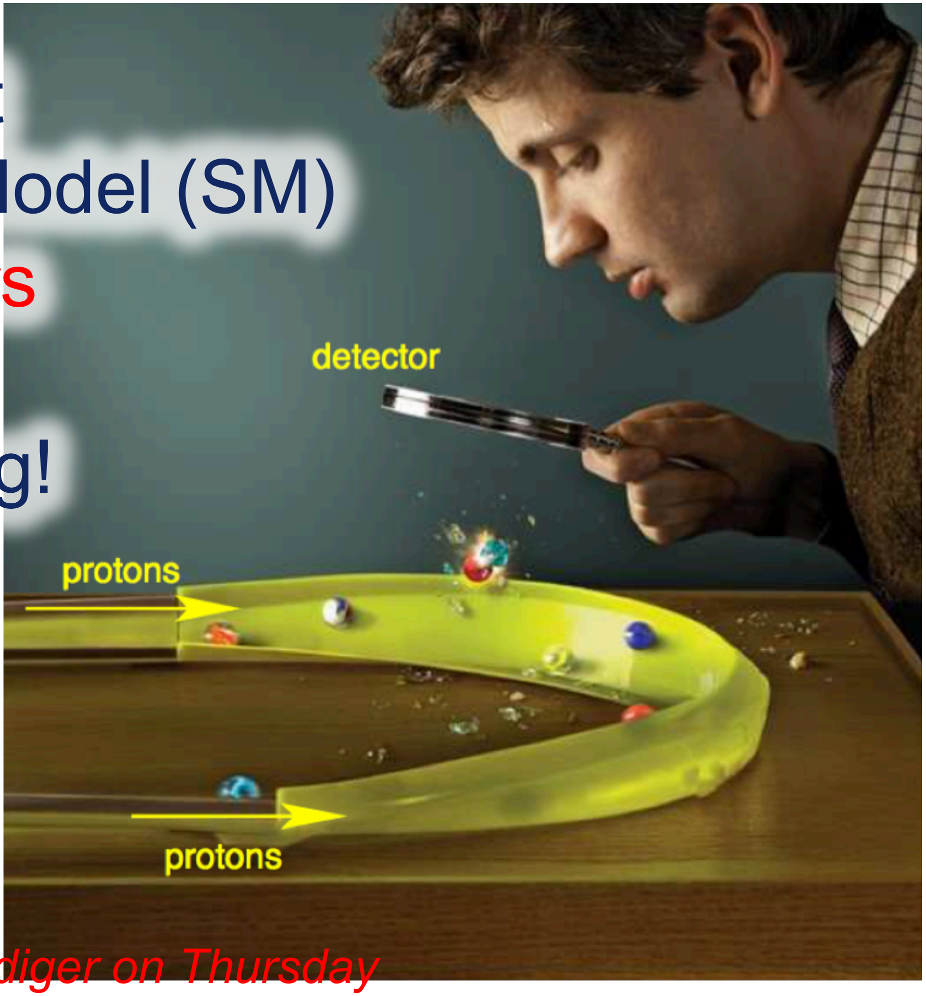
Today: scrutinise the Standard Model with particle accelerators and detectors

Will talk about
1) Standard Model (SM)
2) Accelerators
3) Detectors
in the following!

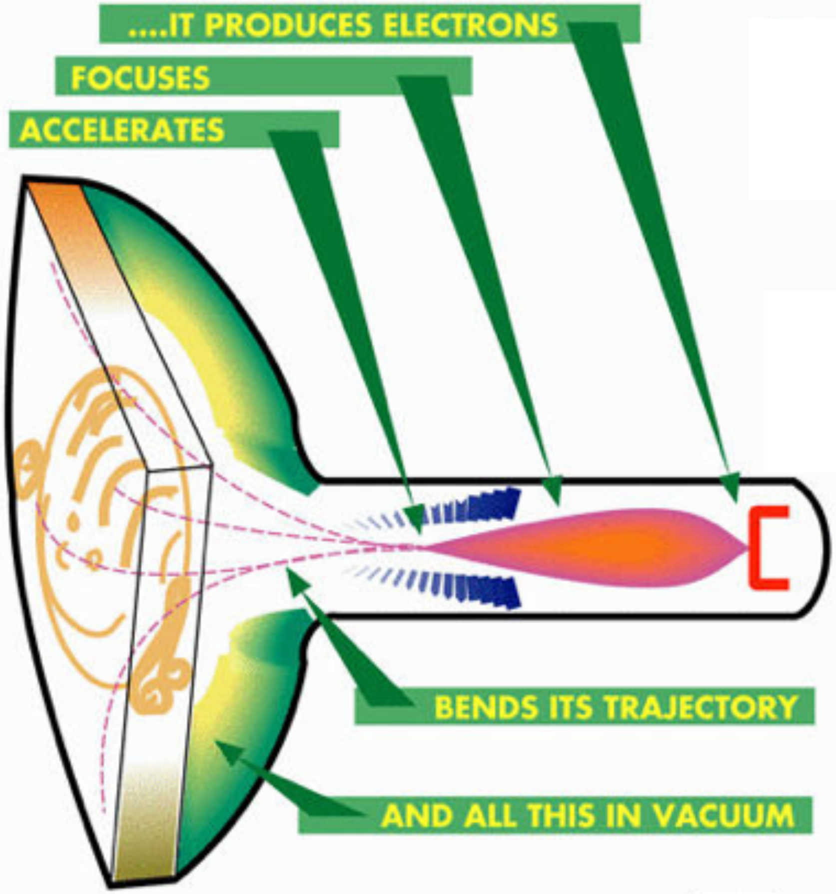


See also lecture by Rüdiger on Thursday

Accelerator principle

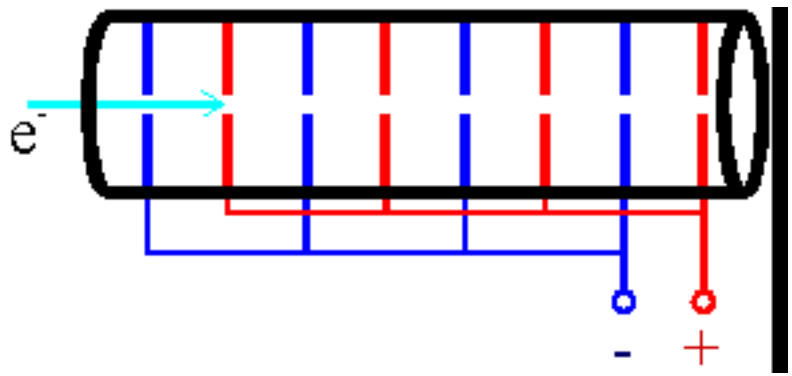
1 eV: energy gain of an electron traversing a potential difference of 1 V

A TV picture tube reaches **20-30 keV**



TV set: **linear accelerator**
(potential difference traversed 1x)

Linear accelerator in particle physics:

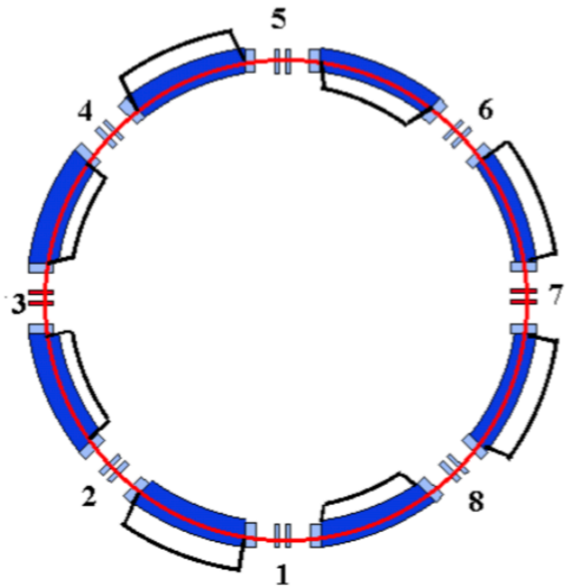


Problem:

→ Acceleration distance of o(thousand km) necessary for the LHC!

Synchrotron accelerator principle

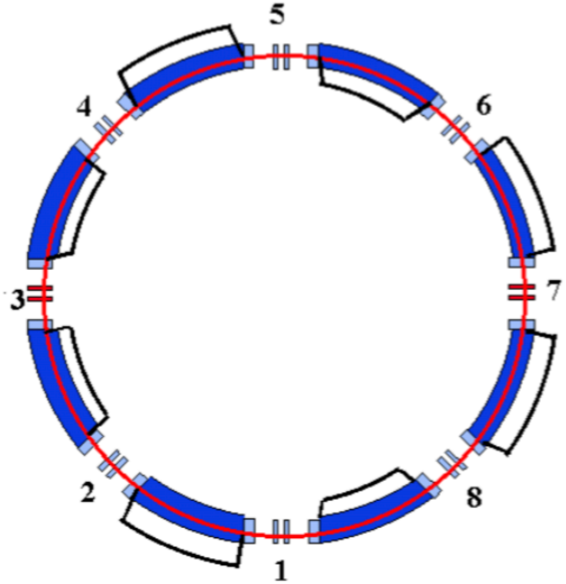
- Solution: **Synchrotron!**
  - Traverse the same potential difference several times!



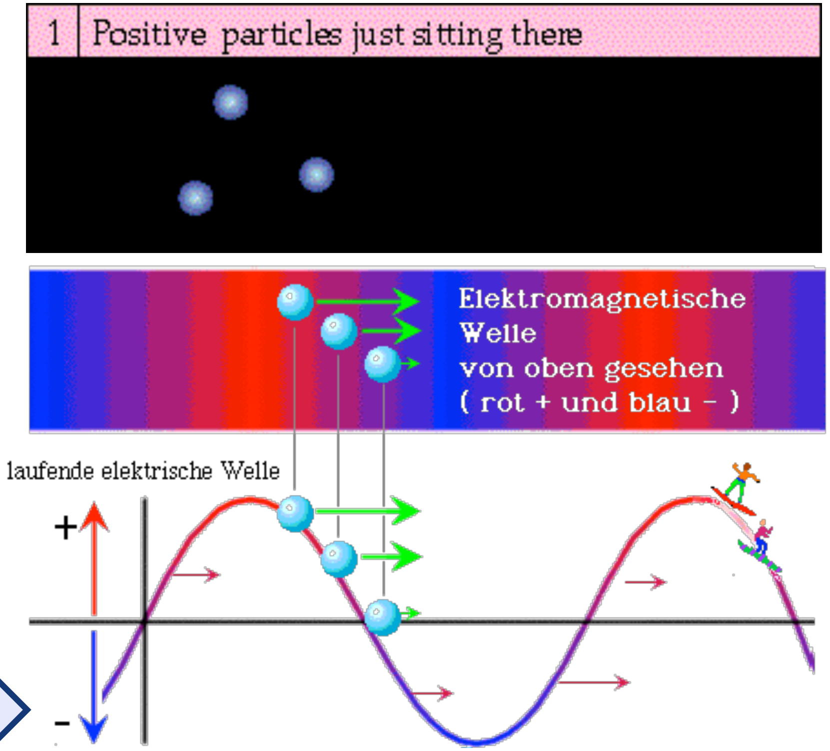
  - Energy conservation?!
    - Protons are almost at light speed
    - → acceleration through "co-running" EM-wave!

Synchrotron accelerator principle

- Solution: **Synchrotron!**
  - Traverse the same potential difference several times!



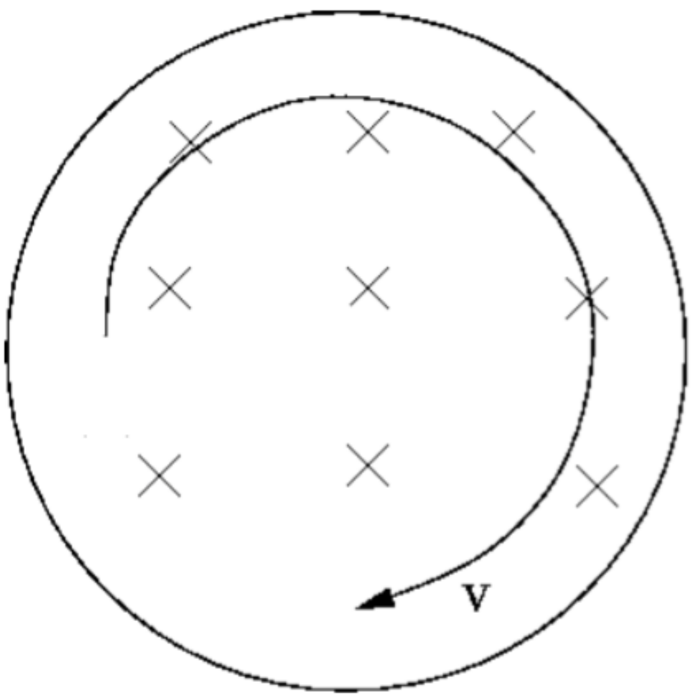
  - Energy conservation?!
    - Protons are almost at light speed
    - → acceleration through “co-running” EM-wave!

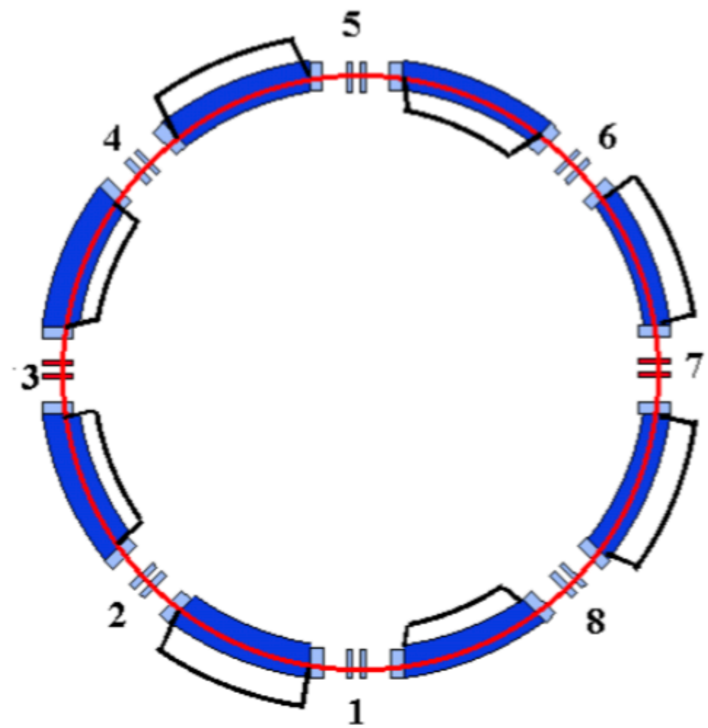


Beam guidance: basic principle

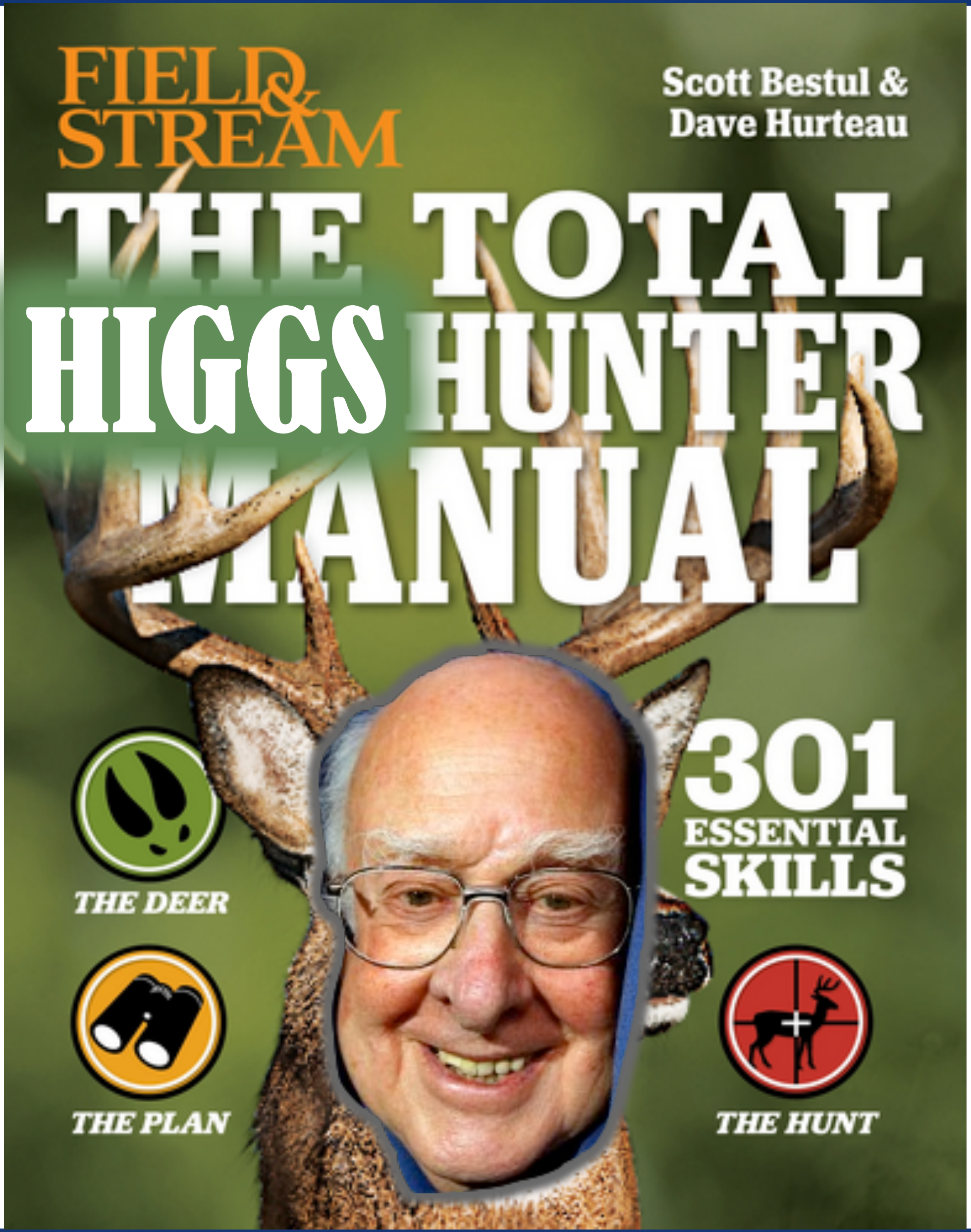
- **Sychrotron:**
  - Beam guidance through deflection of charged particle in a magnetic field (Lorentz-force)

$$\vec{F}_L = q \cdot (\vec{v} \times \vec{B})$$

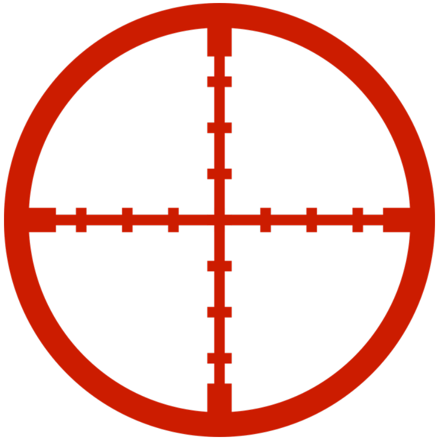




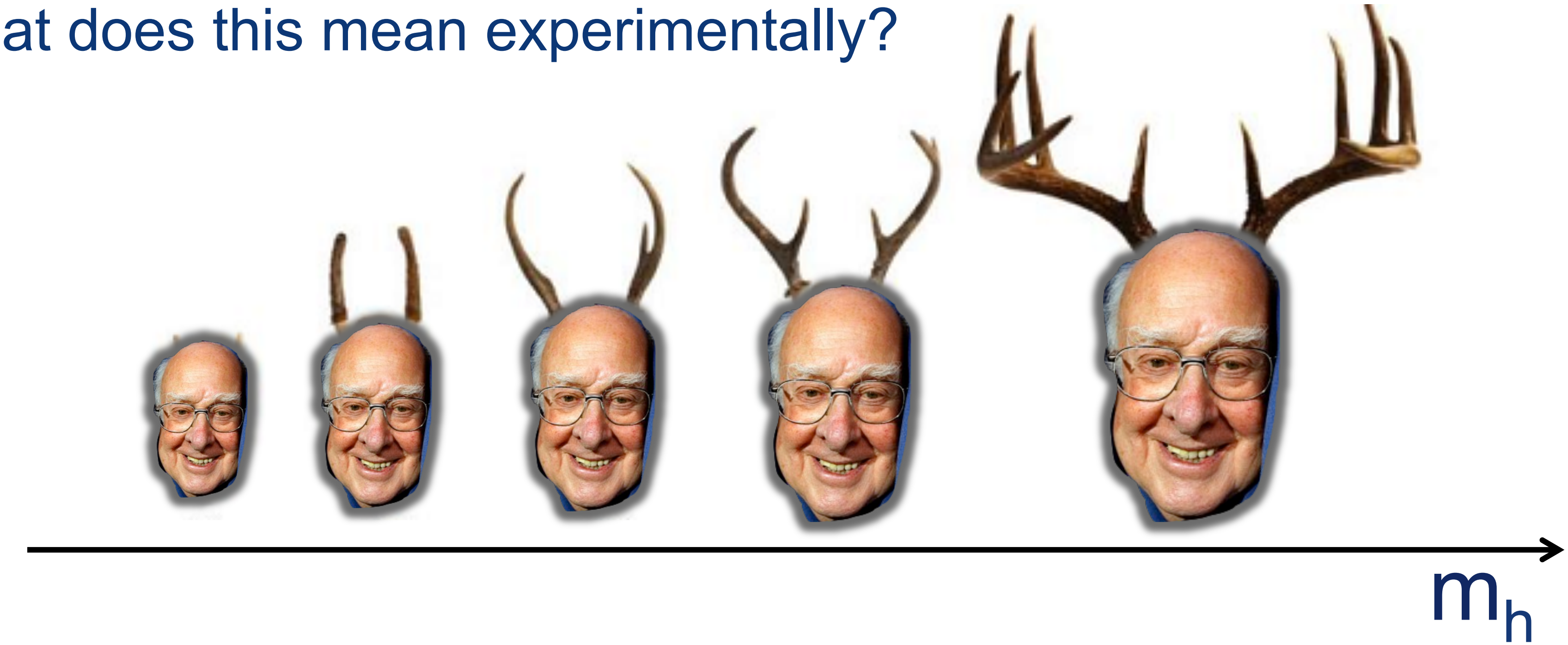
How to hunt for the Higgs boson?



How to hunt for the Higgs boson?

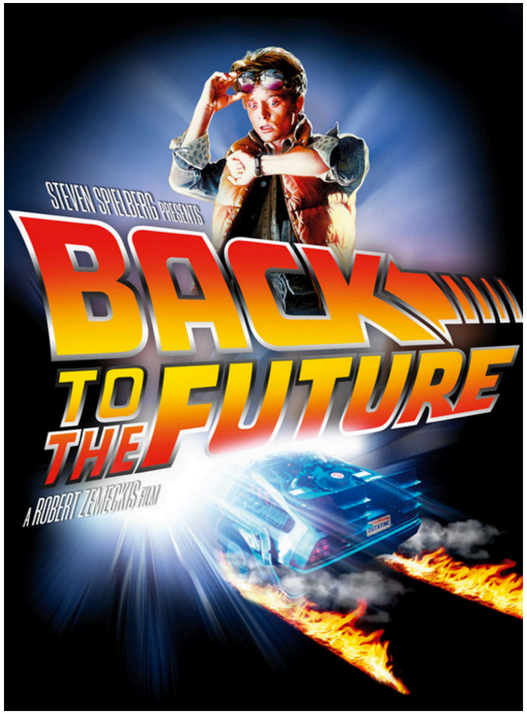


- The SM Higgs mechanism is fully determined
  - The only free parameter is m_h
    - "Free parameter":
      - Measure & put by hand into the SM Lagrangian
- From perturbativity/triviality bounds:
  - $m_h < 1$ TeV
- What does this mean experimentally?



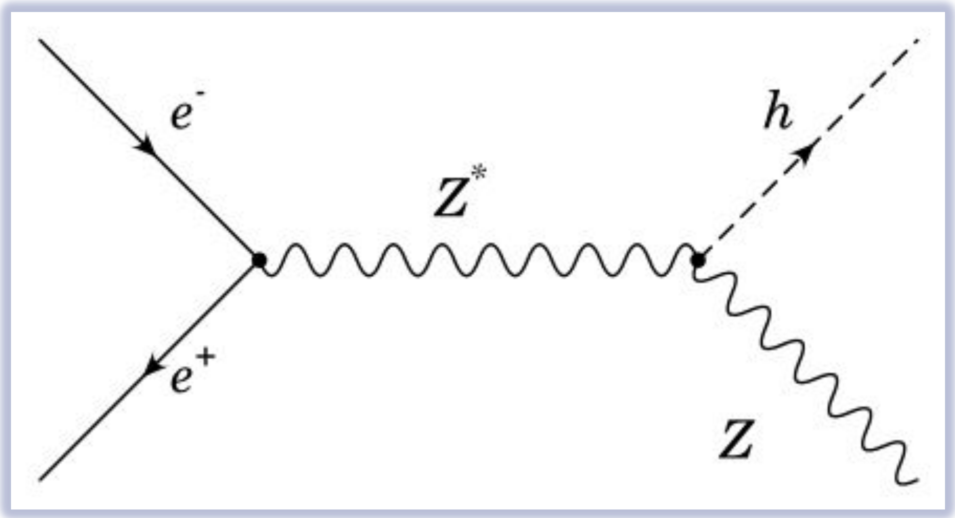
Planning for the Higgs hunt in the 80ies:

- **If m_h < 100 GeV:**
  - Search using e^+e^- colliders
    - E.g. PETRA$_{@DESY}$ ($\sqrt{s}$=50 GeV, existing)
    - LEP1$_{@CERN}$, SLC$_{@SLAC}$ ($\sqrt{s}\approx$100 GeV, under construction)
    - LEP2$_{@CERN}$ ($\sqrt{s}\approx$200 GeV, upgrade planned)
- **If m_h > 100 GeV:**
  - Search using a hadron collider
    - Tevatron$_{@Fermilab}$ ($\sqrt{s}\approx$2 TeV, under commissioning)
    - LHC$_{@CERN}$ ($\sqrt{s}\approx$10-20 TeV, planned)
    - SSC$_{@Waxahachie}$ ($\sqrt{s}\approx$40 TeV, planned)
- Why two different m_h cases?
  - Consider e^+e^- case first



Higgs searches at e^+e^- colliders

- Main search channel at LEP2:
  - associated Zh production



- → Need at least $\sqrt{s} > m_h + m_Z > m_Z \approx 100$ GeV
  - What does this mean experimentally?

Higgs searches at e^+e^- colliders

- **Limiting factor is synchrotron radiation!**
  - Power of synchrotron radiation:

$$P_{\text{synchro}} \propto \frac{\gamma^4}{\rho^2}$$

$$\gamma \equiv \frac{1}{\sqrt{1-\beta^2}}$$

$$\beta \equiv v^2/c^2, \; c \equiv 1$$

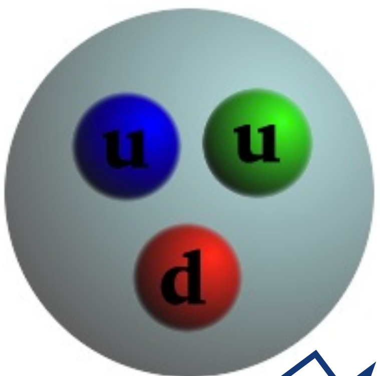
  - E.g., for LEP2 with $\sqrt{s}$=200 GeV:
    - γ = 2 x 10^5, $\varrho \approx$ 3 km
    - $P_{\text{synchro}} \approx 7.5 \times 10^{-6}$ W x 10^{12} electrons ≈ **7.5 MW!**
      - Small-sized powerplant!
  - Can increase ϱ but…
    - ... for ϱ = 3 → 6 km: circumference 28 → 113 km
      - Unfortunately \$\$\$ ∝ circumference (not radius ;))

- Synchrotron radiation small at hadron colliders:
  - √s = 14 TeV:
    - $\gamma = 7.5 \times 10^3$, $\varrho \approx 3$ km (reuse LEP tunnel)
    - $P_{synchro} \approx 1.5 \times 10^{-11}$ W x 10^{14} protons ≈ **1.5 kW!**
      - This is the power of a vacuum cleaner at home
- **Limitation from magnetic field:**
  - B = 8.3 T to keep protons on orbit at the LHC
    - (advanced MRI machines get ≈5 T)
  - Magnets define limitation of √s = 14 TeV!

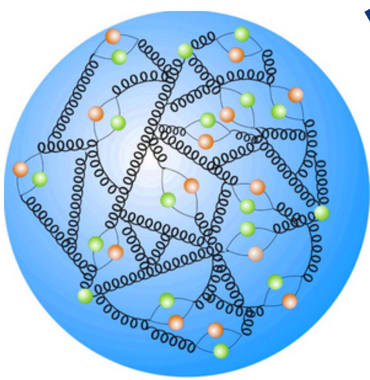
Higgs searches at hadron colliders

- **Another limitation:**
  - $\sqrt{s}$ of the elementary constituents of the proton matters
  - not $\sqrt{s}$ of the proton itself!

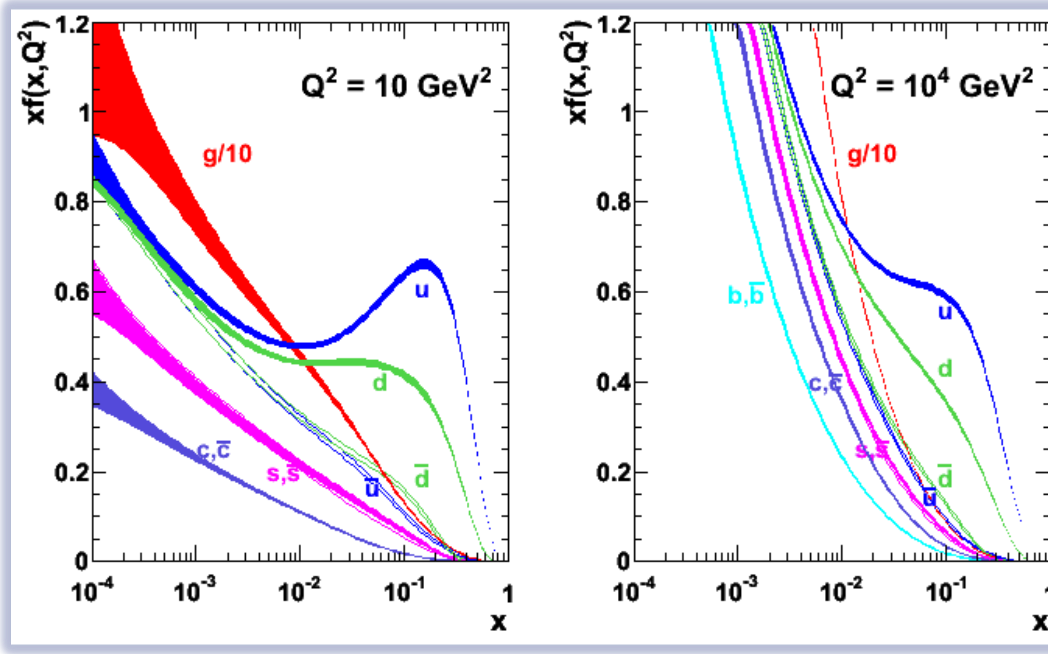
Naïve picture



"Real" picture



Real physics

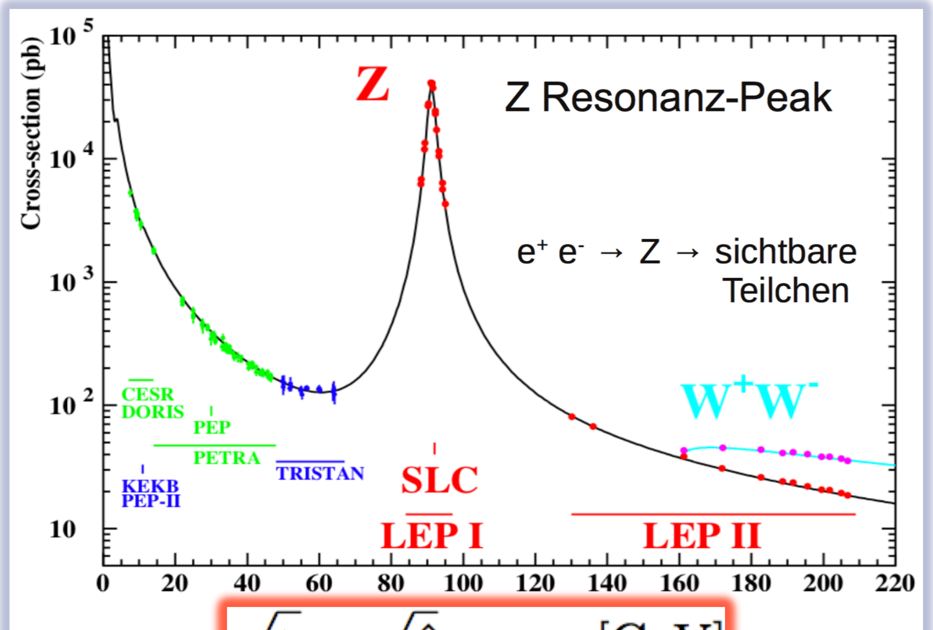


$$\sqrt{s} \gg \sqrt{\hat{s}} = m_h$$

$\sqrt{s}$ = 10 – 20 TeV considered a safe bet for m_h < 1 TeV

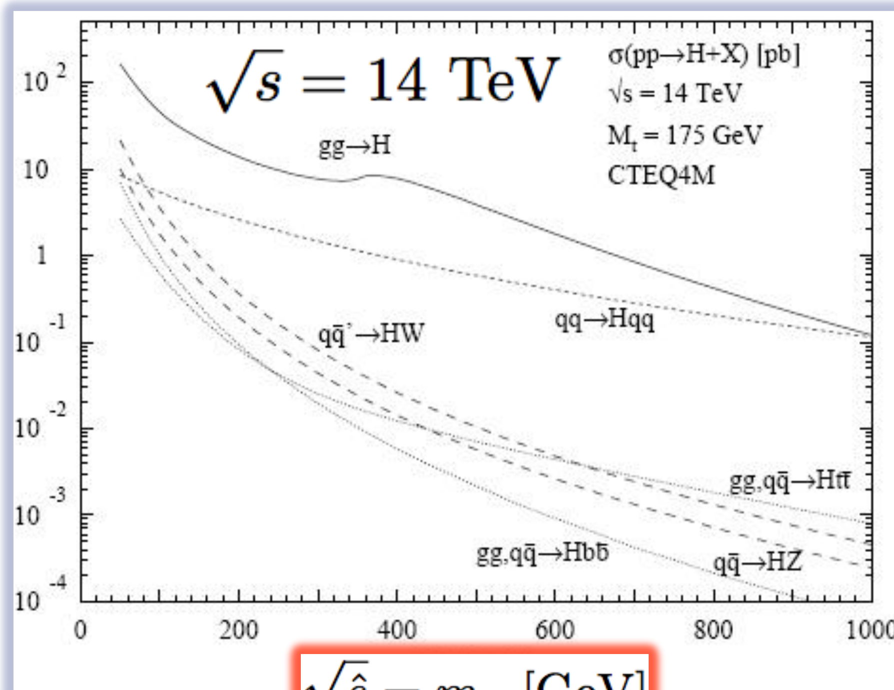
Advantage of new physics searches at hadron colliders:

- At e^+e^- colliders:
  - Search for new physics by scanning $\sqrt{s}$ point by point
    - Example: Z width



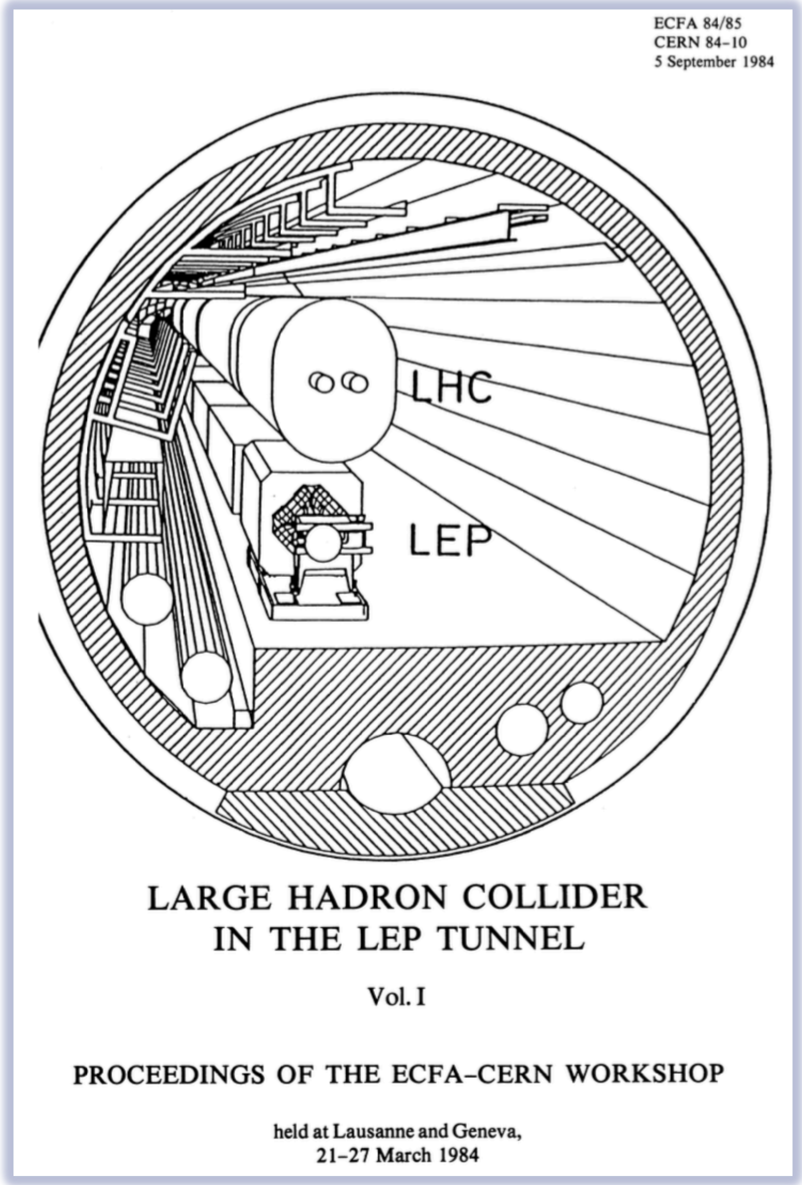
$$\sqrt{s} = \sqrt{\hat{s}} = m_h \ [\text{GeV}]$$

- At hadron colliders:
  - Different $\sqrt{s}$ are covered simultaneously
    - "Switch on and wait"



$$\sqrt{\hat{s}} = m_h \ [\text{GeV}]$$

Planning for the Higgs hunt in the 80ies:


ECFA 84/85
CERN 84-10
5 September 1984

LARGE HADRON COLLIDER
IN THE LEP TUNNEL

Vol. I

PROCEEDINGS OF THE ECFA-CERN WORKSHOP

held at Lausanne and Geneva,
21-27 March 1984

Planning for the Higgs hunt in the 80ies:

from the first LHC planning workshop proceedings

... The successes of particle physics in the 70's and early 80's has provided answers to the old questions such as:

what is the nature of the weak force?
what is the nature of the strong force?
what is the structure of hadrons?

Satisfied with these successes, we have now to face deeper questions such as:

what is the origin of mass?
what kind of unification may exist beyond the standard model?
what is the origin of flavour?
is there a deeper reason for gauge symmetry?

Planning for the Higgs hunt in the 80ies:

from the first LHC planning workshop proceedings

The conclusions which can be drawn are:

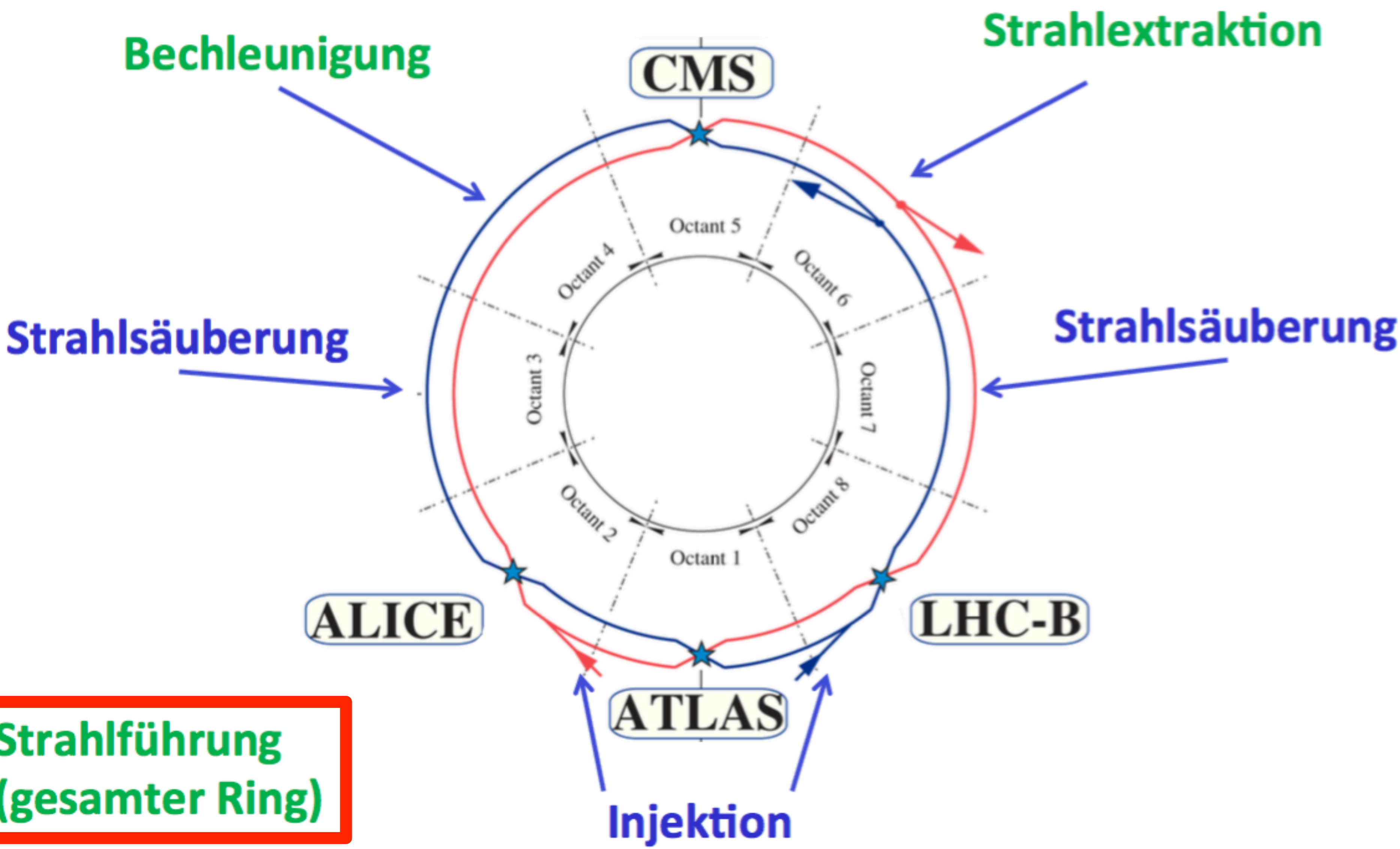
i) A proton-proton collider can be installed in the tunnel above LEP. A centre-of-mass energy of about 18 TeV could be reached with superconducting magnets of 10 T.

ii) In order to achieve this goal, it is necessary to launch in Europe a vigorous programme of development of materials and techniques necessary for the construction of such magnets. Several European Laboratories and Institutions express a great interest to participate in such a programme.

iii) All other machine components and systems appear to be feasible with the present technology.


Large Hadron Collider
~~Campbell's~~
MADE FOR REAL, REAL LIFE.™

Beam guidance



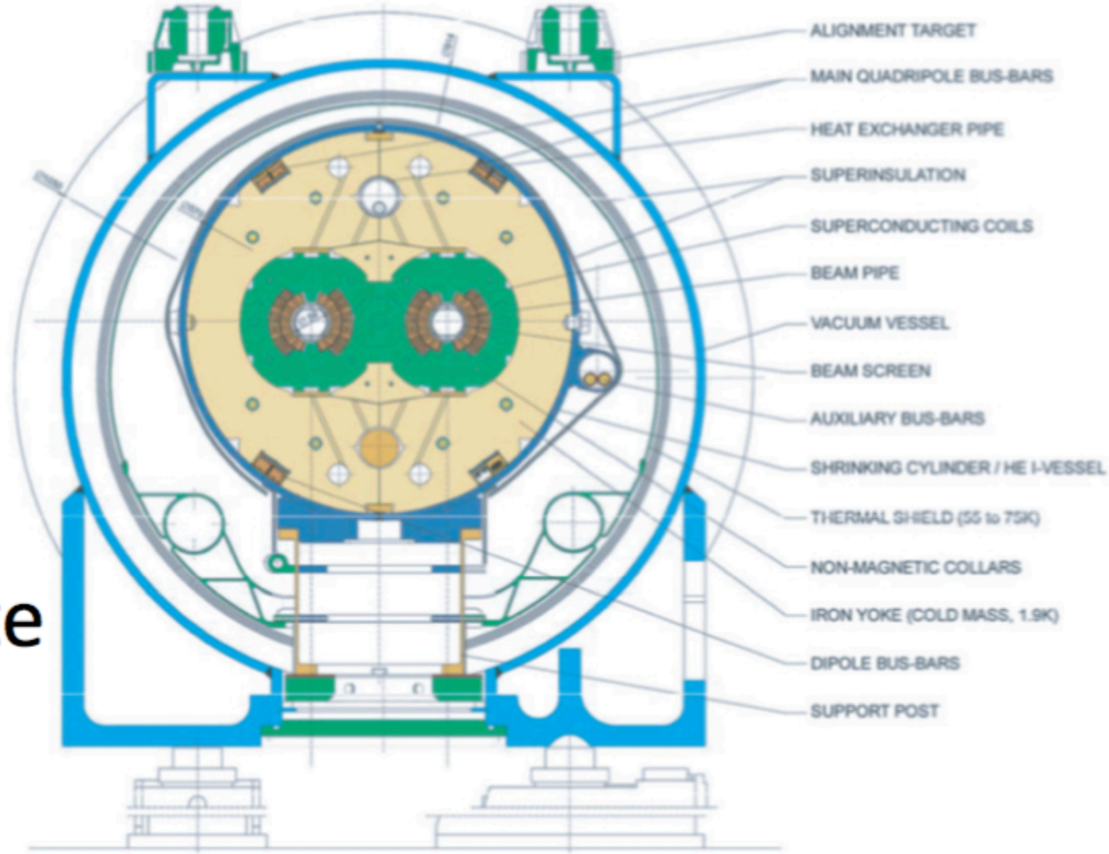
Strahlführung (gesamter Ring)

Beam guidance

- Beam guidance with 1232 superconducting dipole magnets
  - (need superconductivity because I = 12 kA, diesel car battery: 200 A)
- B = 8.3 T with Ni-Ti (~1990)!
  - World record in continuous operation: B = 16.2 T with Nb_3-Sn ('15)

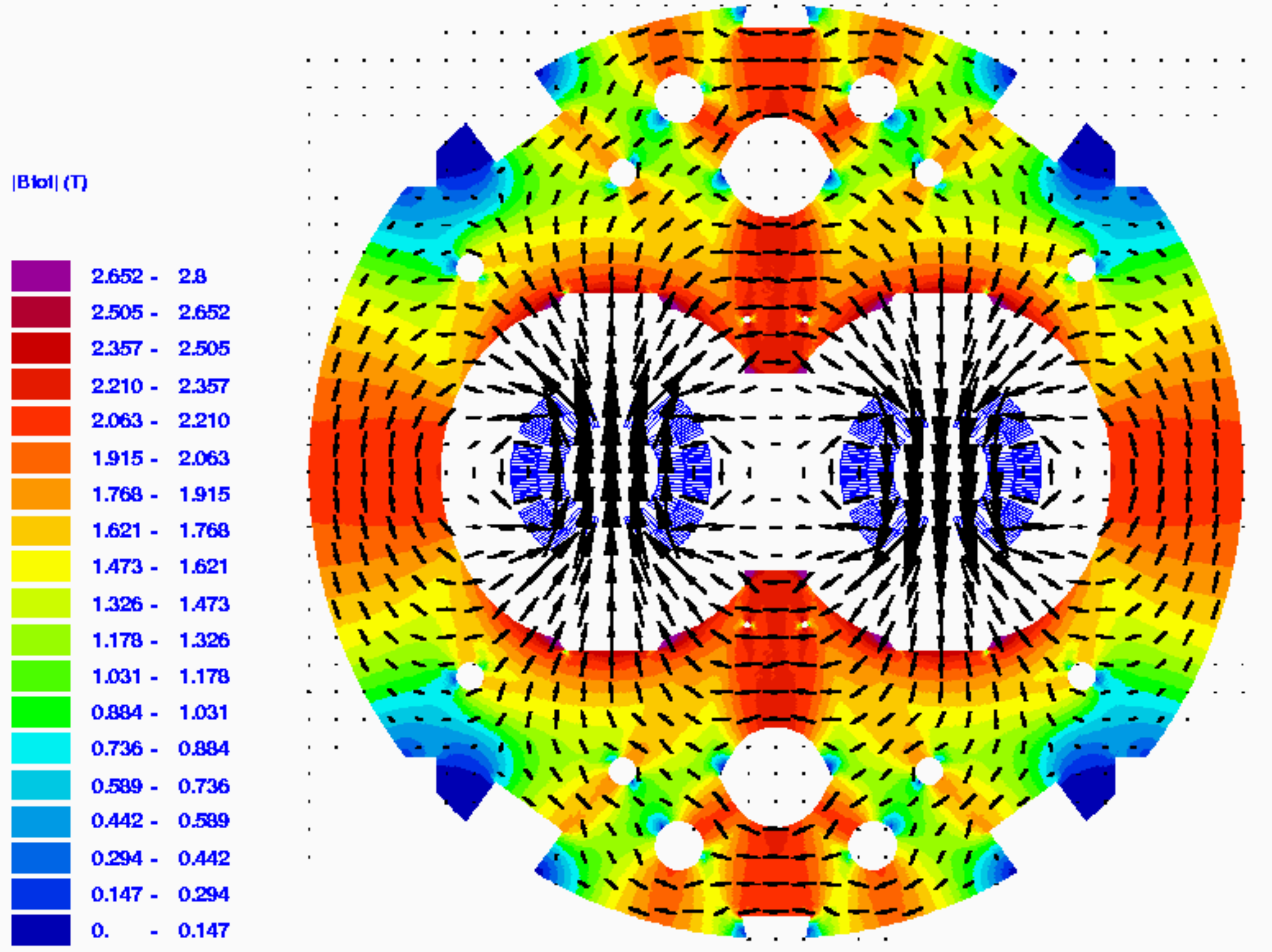
Dipole magnets at LHC

- Das Kernstück des Beschleunigers
- Doppelröhre
- 8.3T Feld
- 12kA Stromstärke
- Supraleitend
- 1.8K Temperatur
- 9.2 GJ gespeicherte Energie



Challenges: mechanics, electronics, cryogenics

Dipole magnets at LHC

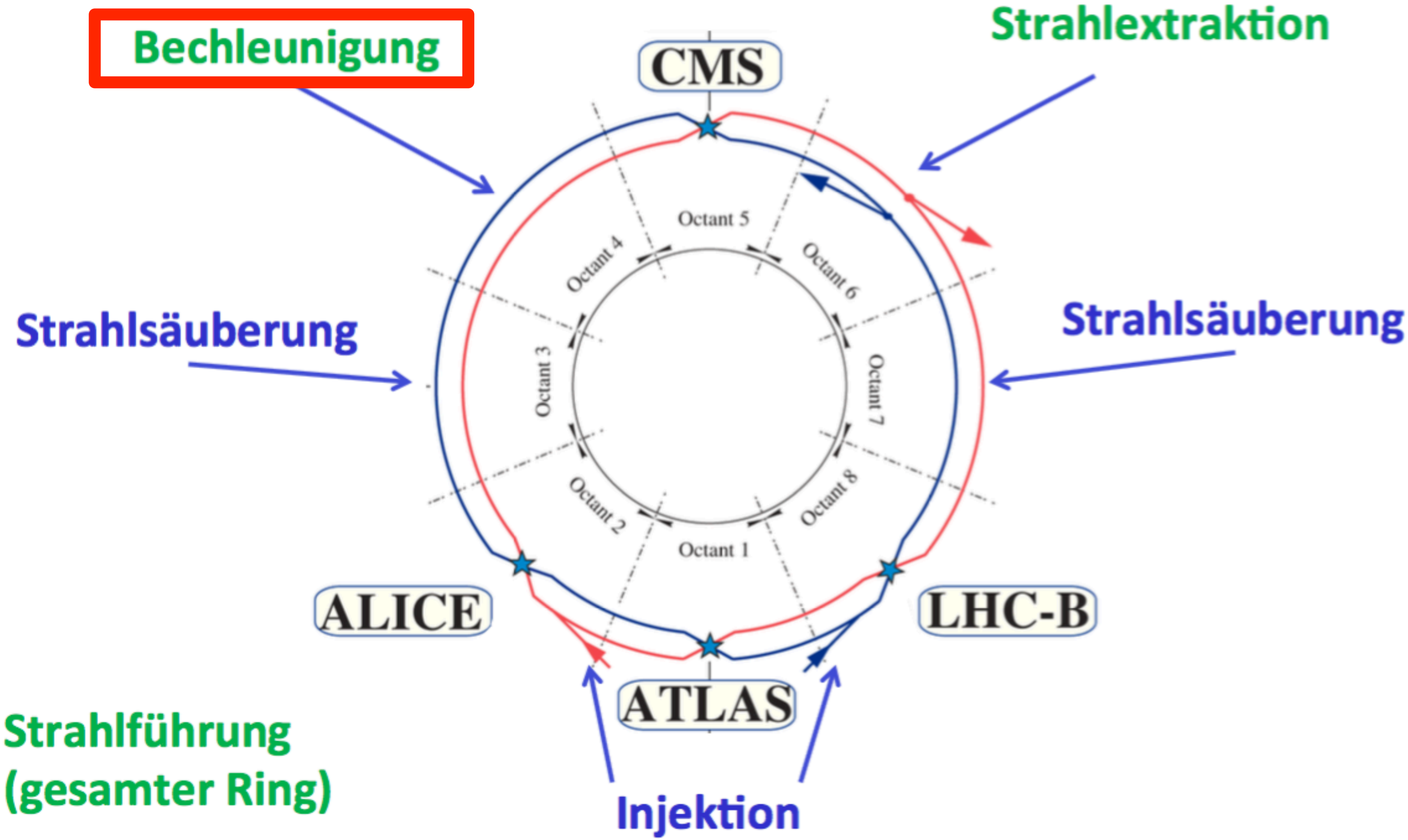


Dipole magnets at LHC

Dipole magnets at LHC

1232 pieces!

Acceleration cavities

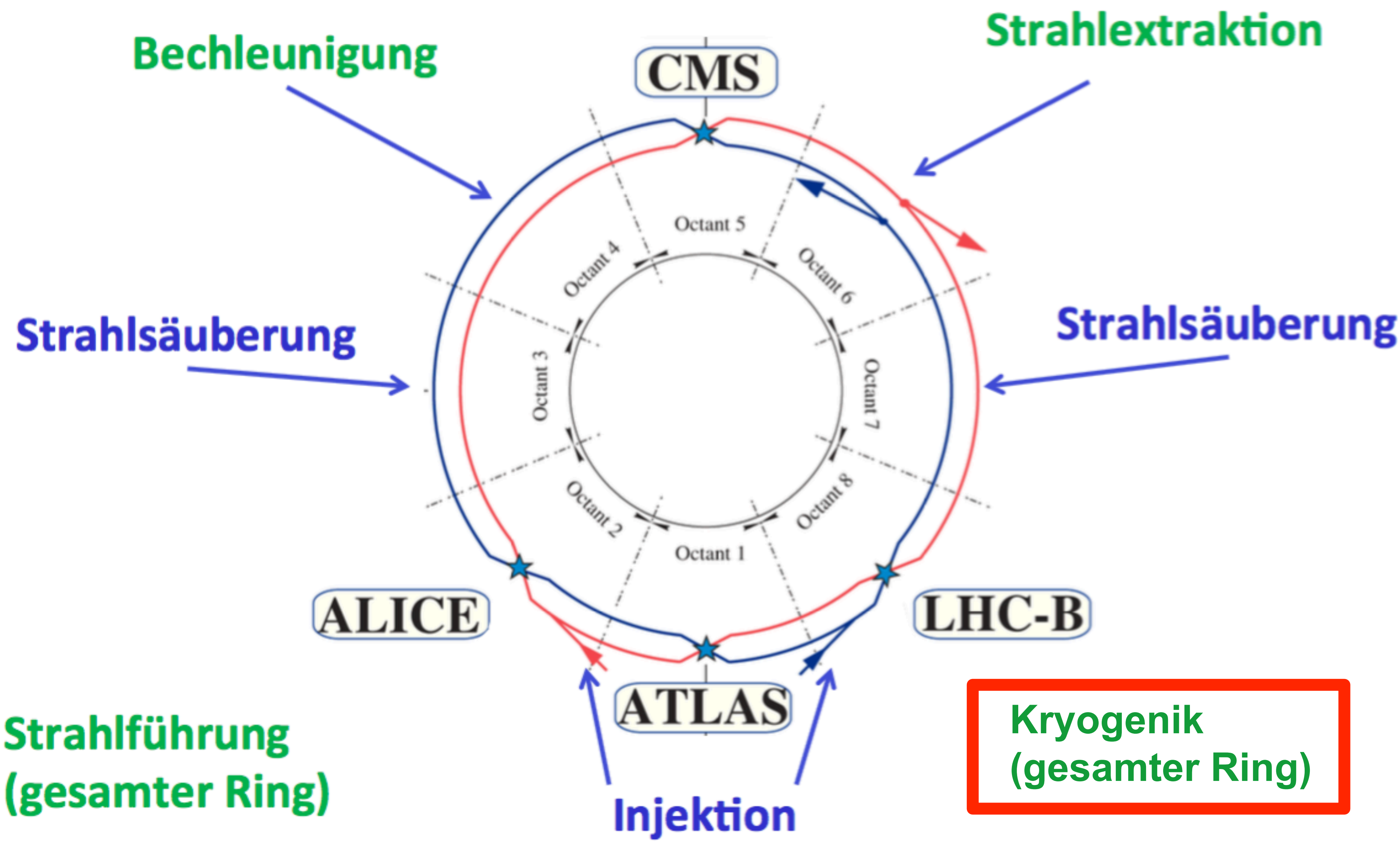


Acceleration cavities

Acceleration cavities using suprconducting technology
- Temperature: 4.5K
- Gradient: 5.5 MV/m (!)
- Power consumption: 300 kW

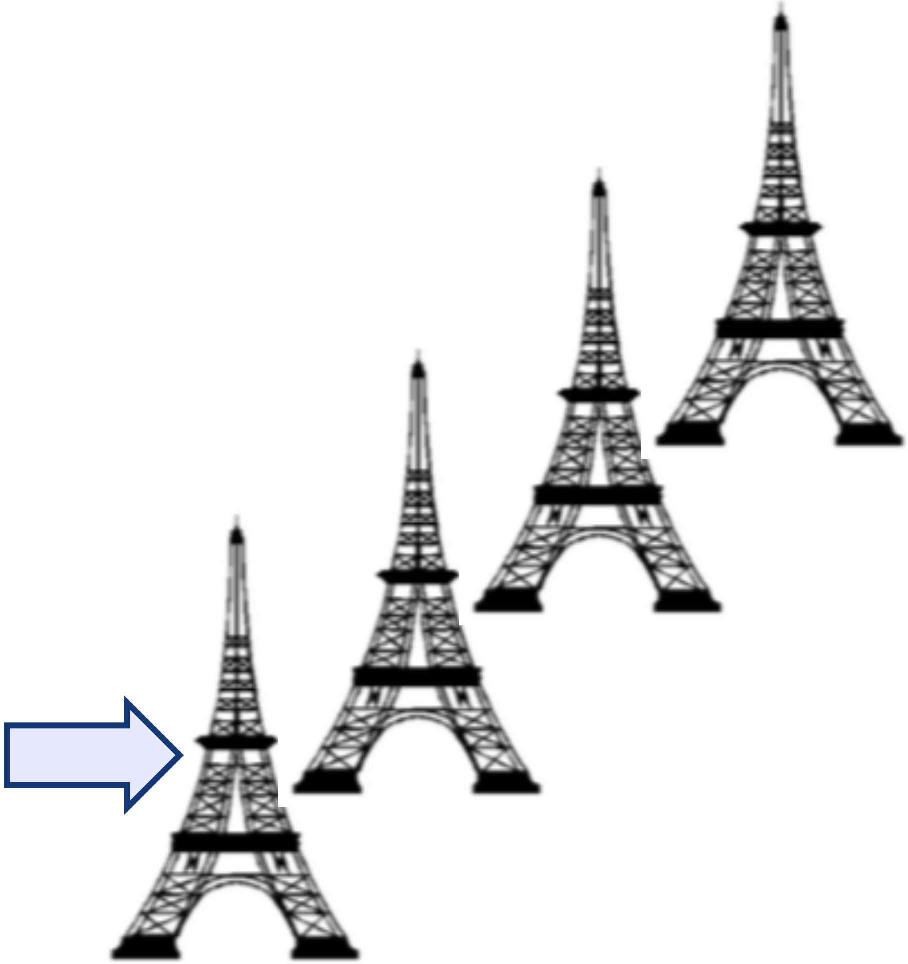
Challenges: fine mechanics, electronics, cryogenics

Cryogenics


Bechleunigung
Strahlextraktion
CMS
Octant 5
Octant 4
Octant 6
Octant 3
Octant 7
Octant 2
Octant 8
Octant 1
Strahlsäuberung
Strahlsäuberung
ALICE
LHC-B
ATLAS
Strahlführung (gesamter Ring)
Injektion
Kryogenik (gesamter Ring)

Cryogenics

- Cryogenics: largest power consumer (40 MW)
  - Acceleration cavities
  - Magnets
  - Experiments
- 3-step cooling process:
  - Liquid nitrogen (80K)
  - Liquid helium (4.5K)
  - Superfluid helium (1.8K)
- Coolant:
  - Liquid nitrogen 10000 tons
  - Liquid helium 120 tons
  - Cold mass 31000 tons



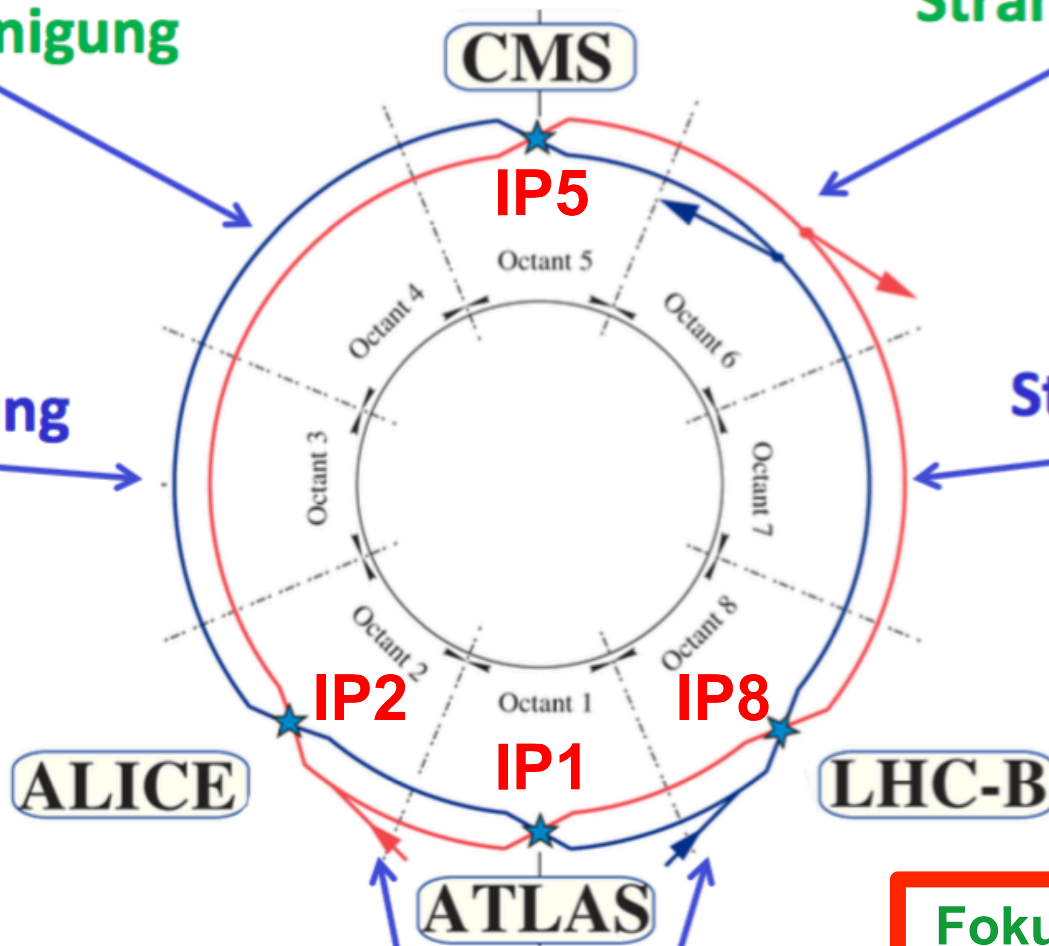
Beam focusing

Bechleunigung

Strahlextraktion

Strahlsäuberung

Strahlsäuberung



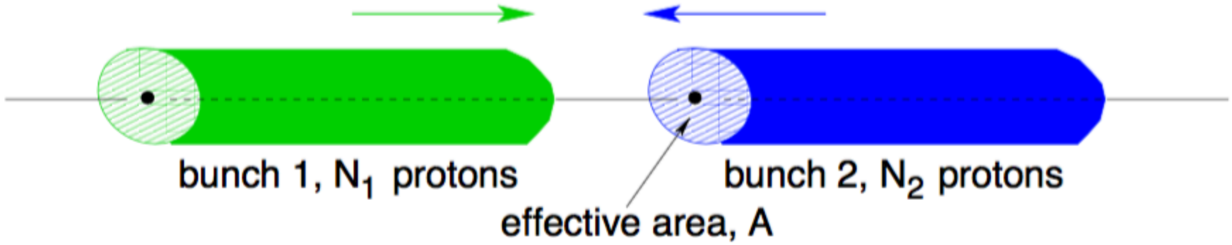
Strahlführung (gesamter Ring)

Injektion

Fokussierung, insbesondere bei IP 1,2,5,8

Beam focusing

LHC: $N_1 \approx 10^{11}$ protons / bunch x 2808 bunches
the larger, the better!



$$\mathcal{L} = \frac{N_1 \cdot N_2 \cdot f}{A}$$

The smaller, the better!
LHC: $A \approx \pi \cdot 10^2\ \mu m^2$

Higher Luminosity → more "interesting" events:

$$N = \int \mathrm{d}t\, \mathcal{L} \cdot \sigma$$

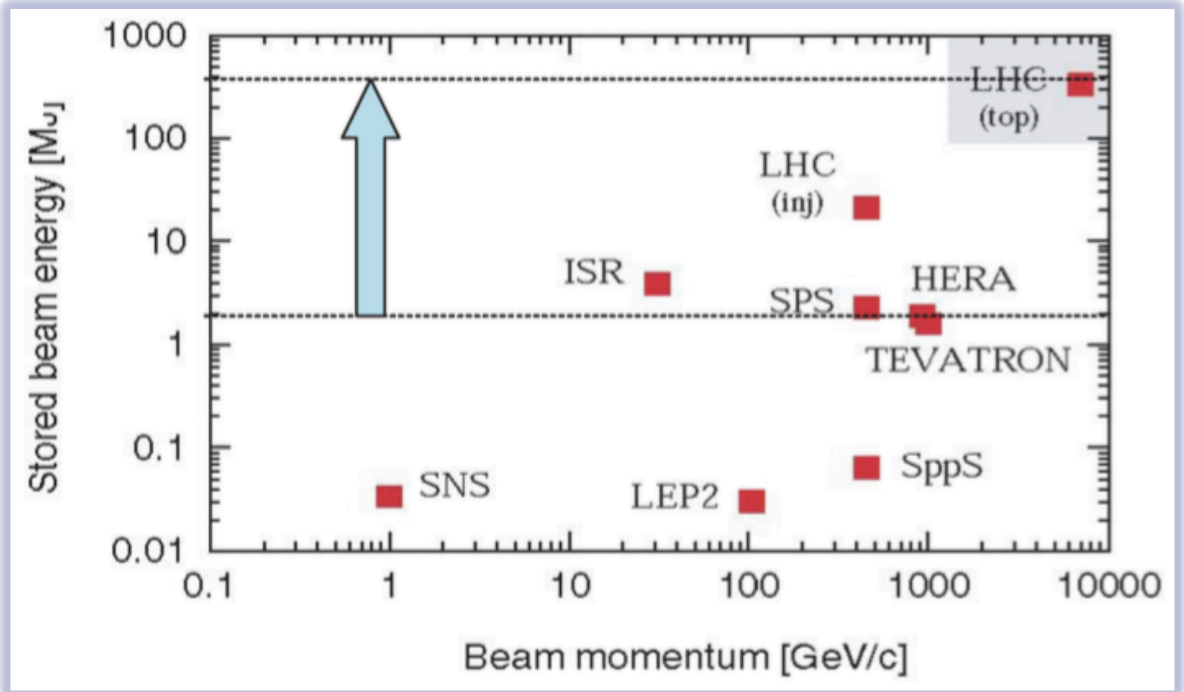
N = number of events (e.g. Higgs events)

σ = cross section (e.g. for Higgs production) [barn=10^{-28} m^2]

$\int \mathrm{d}t\, \mathcal{L}$ = total luminosity

Challenge: focusiing of 10^{11} protons into a small effective area (magnets + steering)

Total beam energy



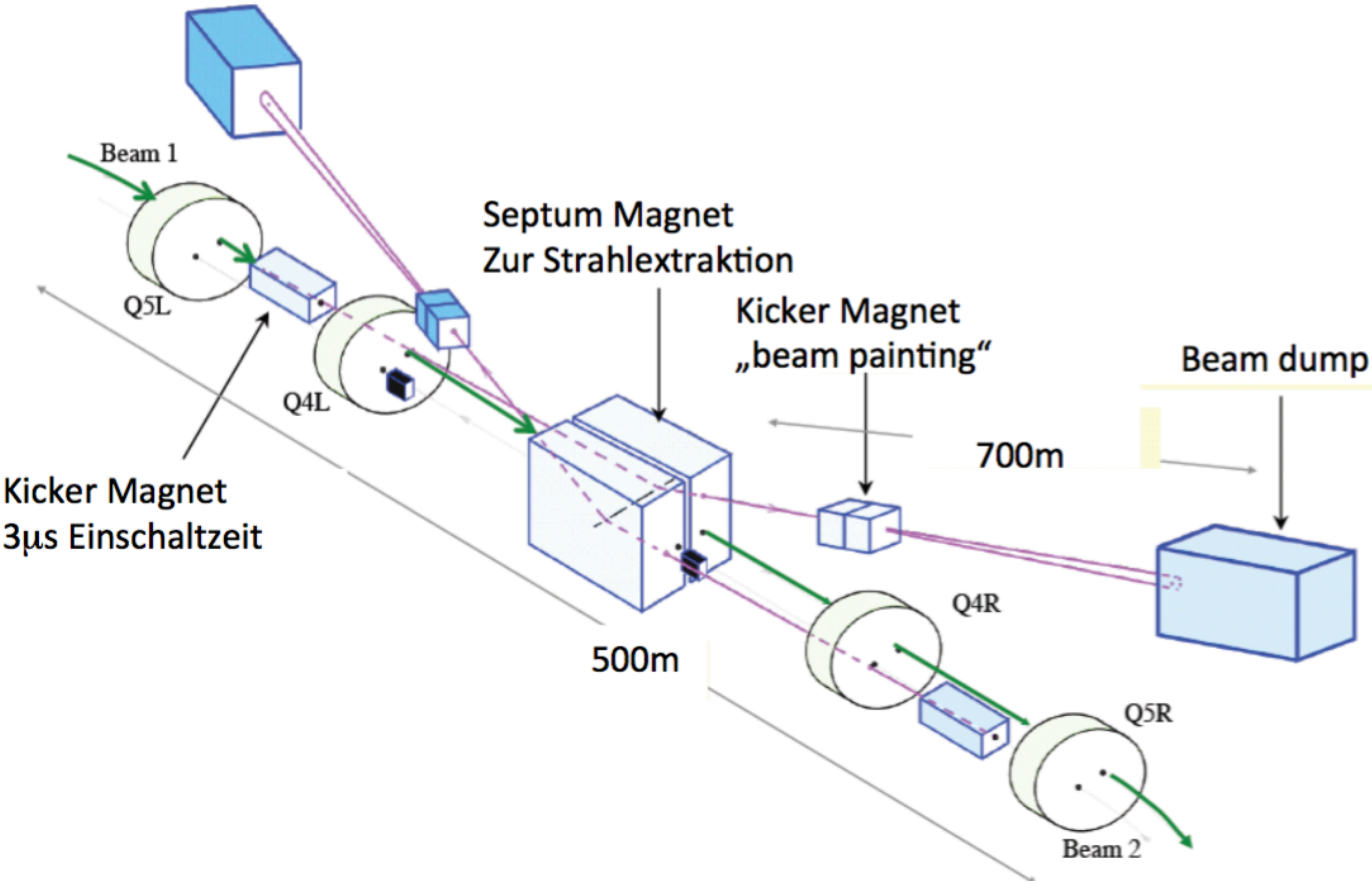
ICE mit 150 km/h

Beam energy: 360 MJ

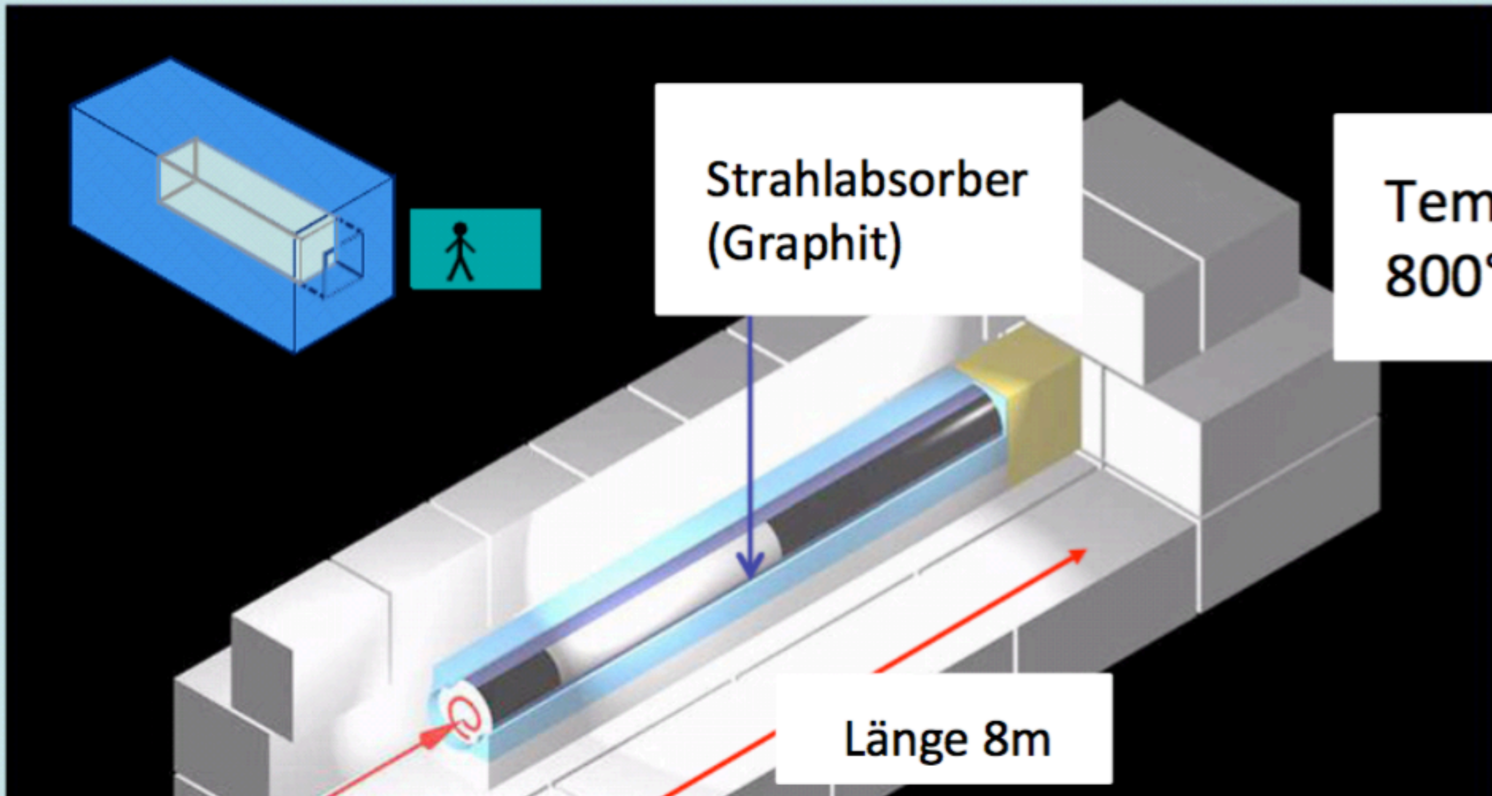
Challenge: control orbit with mm precision

LHC sensitive to:
- Tidal forces (deformation ca. 1mm → adjust!)
- earthquakes (the last largest earthquake in Chile "measured" at LHC!

Total beam energy

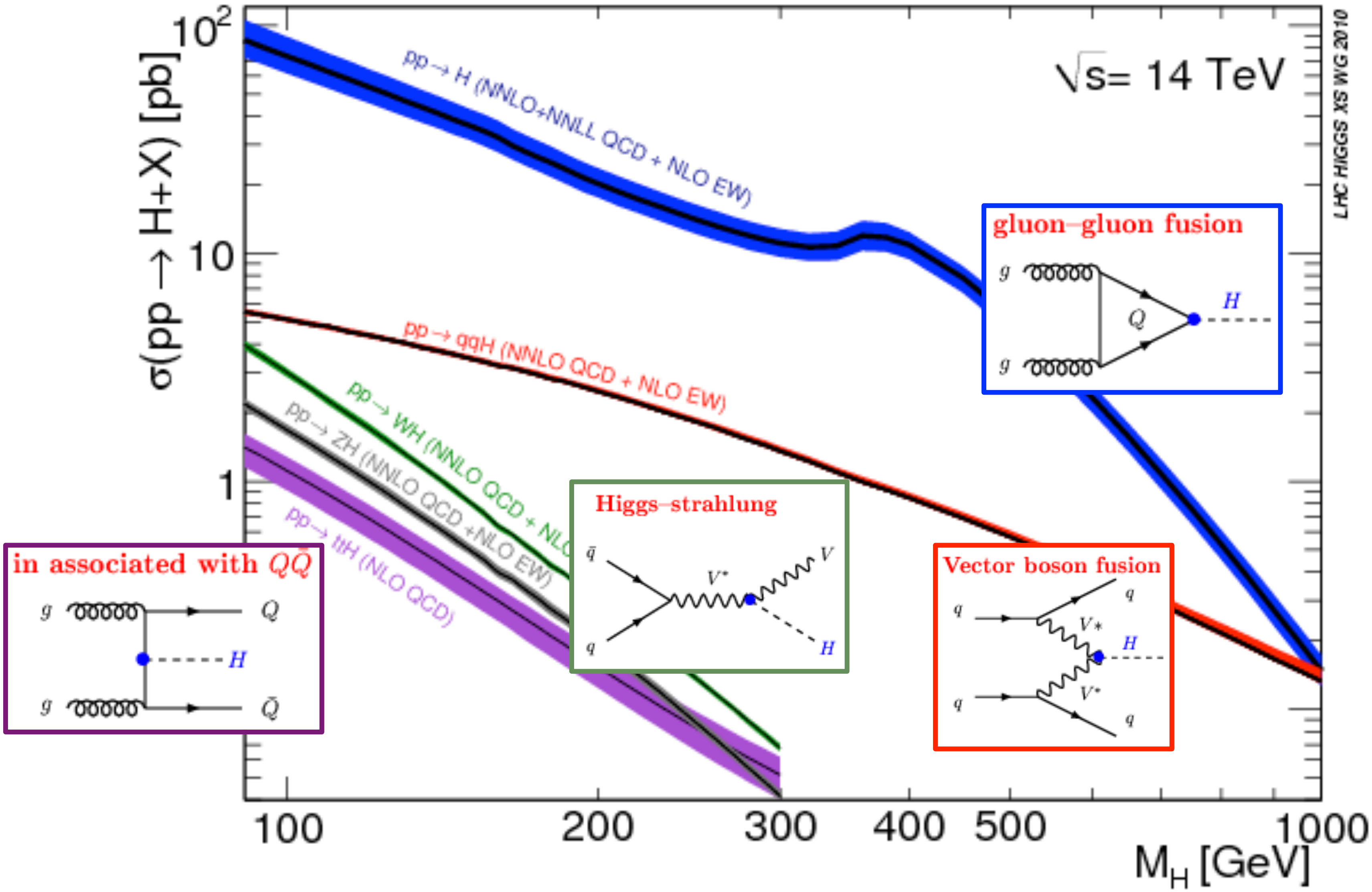


Total beam energy



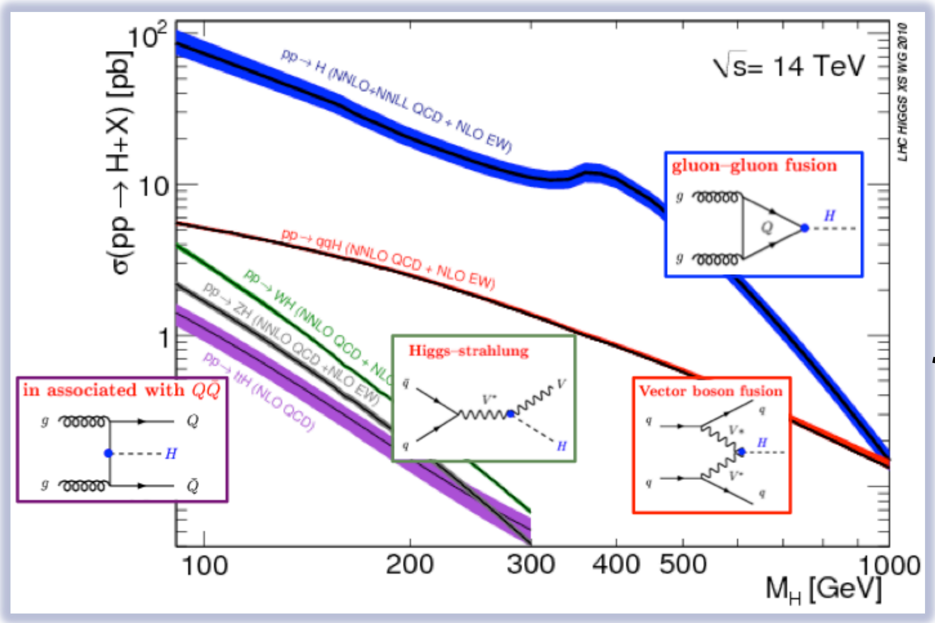
Temperaturanstieg:
800°C

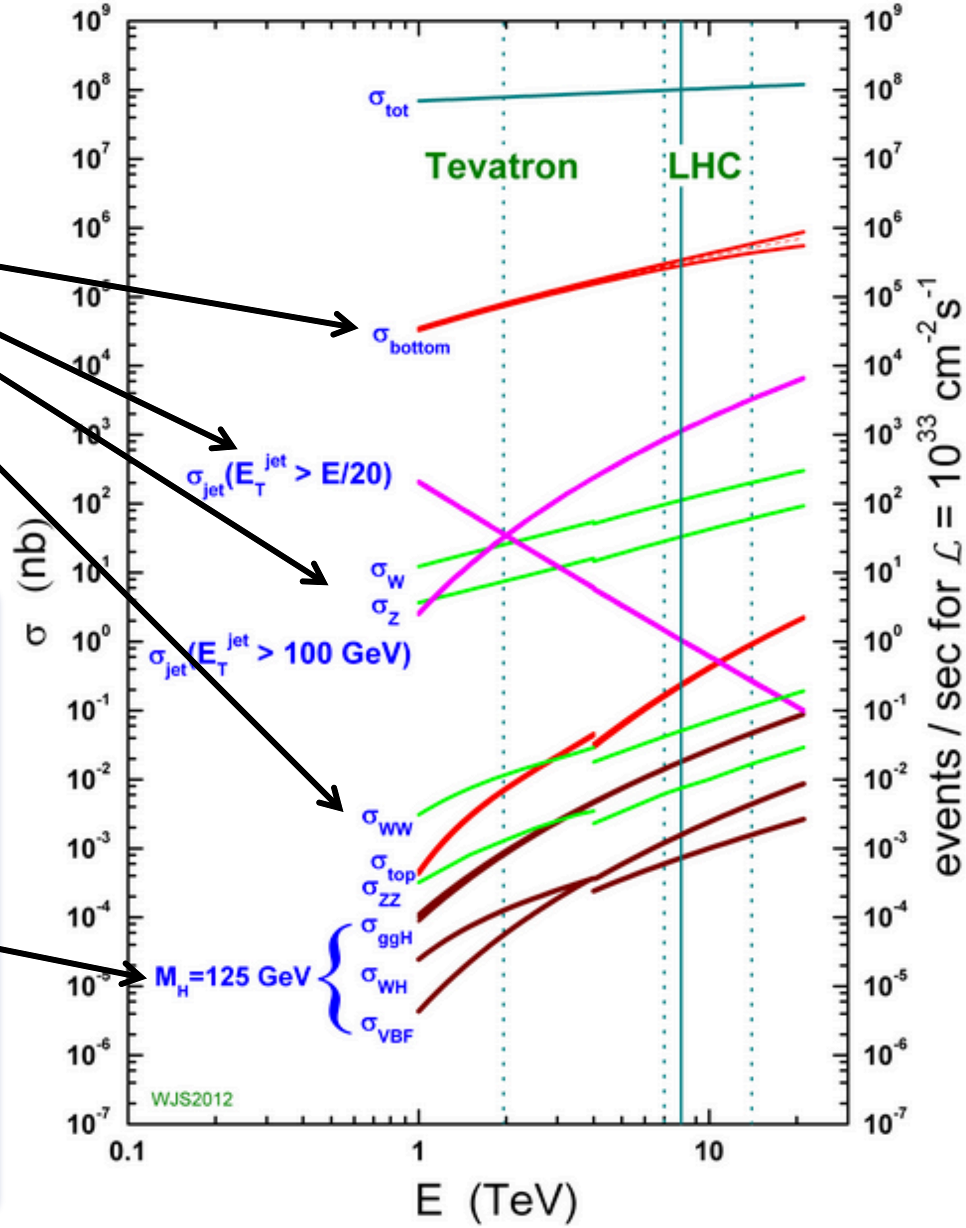
Higgs production at the LHC



Higgs production at the LHC

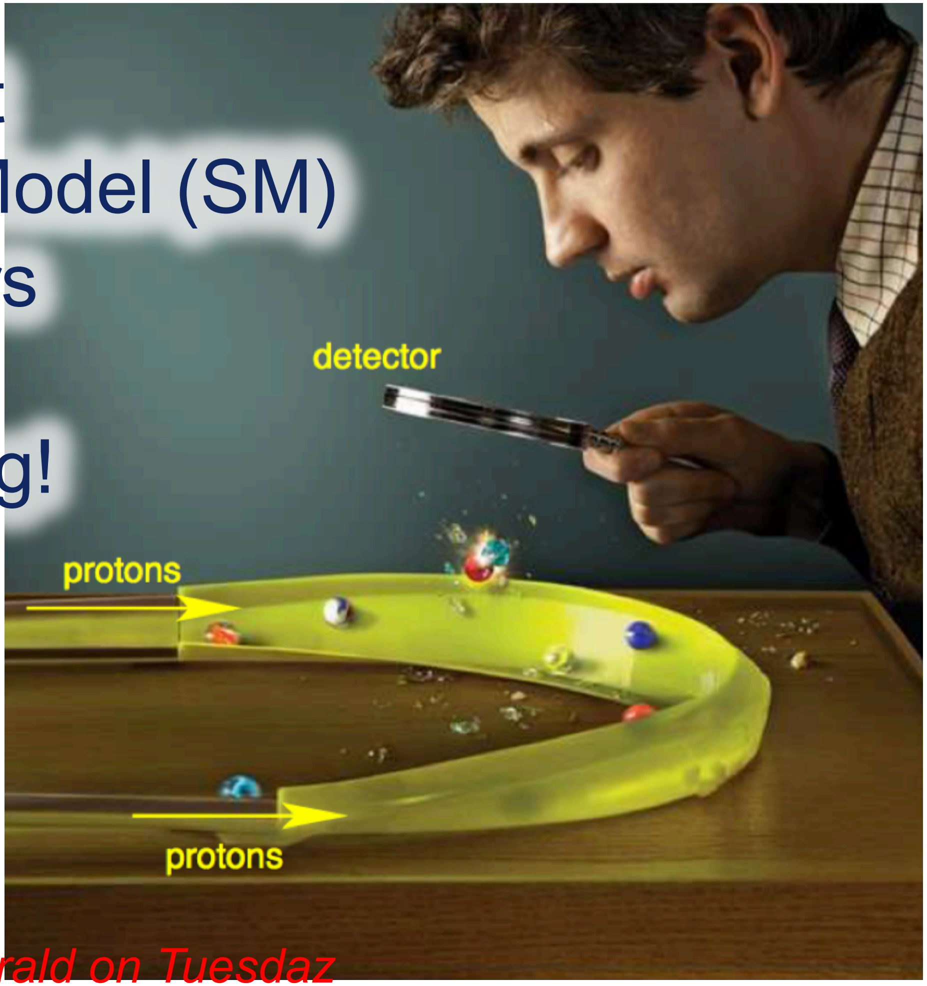
Orders of magnitude larger backgrounds!





Today: scrutinise the Standard Model with particle accelerators and detectors

Will talk about
1) Standard Model (SM)
2) Accelerators
3) Detectors
in the following!



See also lecture by Gerald on Tuesdaz